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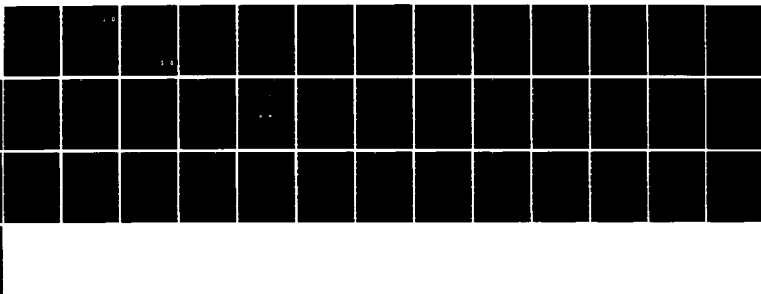
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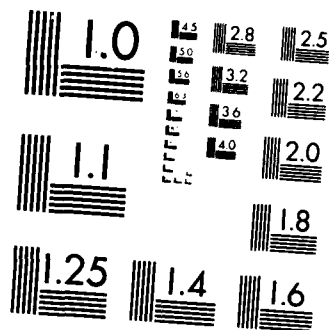
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FINAL PROGRESS REPORT FOR
GRANT AFOSR-84-0025

"POPULATION INVERSION AND GAIN MEASUREMENTS FOR
SOFT X-RAY LASER DEVELOPMENT IN A
MAGNETICALLY CONFINED PLASMA COLUMN"

For the Period:

Nov. 1, 1983 thru Sept. 30, 1985

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Submitted to the
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REPORT DOCUMENTATION PAGE

AD-A173232

1a REPORT SECURITY CLASSIFICATION Unclassified			1b RESTRICTIVE MARKINGS											
2a SECURITY CLASSIFICATION AUTHORITY			3 DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution unlimited.											
2b DECLASSIFICATION DOWNGRADING SCHEDULE														
4 PERFORMING ORGANIZATION REPORT NUMBERS			5 MONITORING ORGANIZATION REPORT NUMBERS AFOSR-TR- 86-0825											
6a NAME OF PERFORMING ORGANIZATION Princeton University		6b OFFICE SYMBOL (If applicable)		7a NAME OF MONITORING ORGANIZATION AFOSR										
6c ADDRESS (City, State and ZIP Code) Plasma Physics Laboratory Princeton, NJ 08544				7b ADDRESS (City, State and ZIP Code) Building 410 Bolling AFB DC 20332-6448										
8a NAME OF FUNDING SPONSORING ORGANIZATION AFOSR		8b OFFICE SYMBOL (If applicable) NP		9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER AFOSR 84-0025										
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12 PERSONAL AUTHOR(S) Dr Simon Suckewer														
13a TYPE OF REPORT FINAL		13b TIME COVERED FROM 1 Nov 83 TO 30 Sep 85		14 DATE OF REPORT (Yr Mo Day) 15 Sep 1985										
15 PAGE COUNT 45														
16 SUPPLEMENTARY NOTATION														
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19 ABSTRACT (Continue on reverse if necessary and identify by block number) During the 23 months of AFOSR funding under this grant, the following was accomplished in the x-ray laser experiments underway at the Princeton Plasma Physics Lab: 1) A new optical system was built for the CO ₂ laser which allowed an order of magnitude higher power density in the focal plane. 2) The time evolution of the laser pulse was improved. 3) Work continued on the jet-stream gas target. 4) A number of carbon targets were developed and tested. 5) EUV axial and transverse instruments were modified for measuring line intensities as a function of time. 6) Modifications were made to the computer simulation code, and 7) Single pass gains of between 2.8 and 3.5 were made for various carbon targets.														
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22a NAME OF RESPONSIBLE INDIVIDUAL Dr Robert J. Barker		22b TELEPHONE NUMBER (Include Area Code) 202/767-4908		22c OFFICE SYMBOL NP										

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ABSTRACT

During the twenty-three months of AFOSR funding under this grant, the following was accomplished in the x-ray laser experiments underway at the Princeton Plasma Physics Lab: (1) A new optical system was built for the CO-2 laser which allowed an order of magnitude higher power density in the focal plane, (2) The time evolution of the laser pulse was improved, (3) Work continued on the jet-stream gas target, (4) A number of carbon targets were developed and tested, (5) EUV axial and transverse instruments were modified for measuring line intensities as a function of time, (6) Modifications were made to the computer simulation code, and (7) Single pass gains of between 2.8 and 3.5 were made for various carbon targets.



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Objectives for the two year program were: (Please see summary of the Experimental Program of the proposal to AFOSR entitled "Population Inversion and Gain Measurements for X-Ray Laser Development in Magnetically Confined Plasma Column," Princeton, March 7, 1983)

- (1) To determine conditions for maximizing population inversions in hydrogen-like CVI ions in a confined plasma column as a function of the initial conditions for gas target and solid targets.
- (2) As in (a) but for the Li-like ions CIV, OVI, FVII, NeVIII, ArXI, and SiXII.
- (3) To determine conditions for maximum gain by examining time evolution of level populations.

- (4) To determine the optimum magnetic field, plasma density and column length for obtaining lasing action at the 182\AA $3 + 2$ transition in CVI.
- (5) To determine conditions for population inversion in the hydrogen-like ions OVIII, FIX, and NeX.

To meet the above objectives, the following tasks were planning to be performed in two-year program:

- (a) Development of a new optical system (internal and external) for the CO_2 laser to obtain much higher power/ cm^2 (i.e. improve focussing).
 - (b) Develop a system to obtain a "clean" CO_2 laser pulse without a tail, and with shorter rise and decay times than currently available.
 - (c) Develop a method to create a high pressure gas target in a short time ($t \approx 100 - 200$ nsec) and with a limited length $l \approx 10 - 20$ cm.
 - (d) Develop carbon, fluorine, aluminum and silicon targets with different configurations.
 - (e) Modification of the axial EUV monochromator (Minuteman grazing incidence 1m monochromator) and transverse duochromator (soft x-ray monochromator - spectrometer, SOXMOS) for the installation of fast detectors to measure line intensities in the axial and transverse directions with time resolution $\Delta t \approx 10 - 20$ nsec.
- Calibration of the above instruments for

wavelengths and absolute intensities.

Calibration of the EUV duochromator (spectral region 10 - 350Å) will be provided by the branching ratio technique in situ, and independently by comparison of line intensities obtained on a tokamak plasma using this instrument and another instrument previously calibrated with synchrotron radiation. The Minuteman EUV monochromator (Spectral region 10 - 400Å) will also be calibrated by the branching ratio technique in situ as well as by comparison with line intensity measurements obtained using a similar instrument built by McPherson which will be calibrated on a separate soft x-ray source.

- (f) Modification of the computer code for the analysis of experimental results for hydrogen-like ions and development of a code for the Li-like sequence.
- (g) Conduct 6 month experiment with various solid carbon targets:
 - Disc target with 0.5 mm and 1 mm hole in center
 - Disc target with a 1 mm hole in the center and a carbon filament 10 μ - 20 μ diameter and 1-2 cm long, attached to the edge of the hole.
 - Disc target with a 1 mm hole in center and a razor type carbon blade with different edge thicknesses (between 20 μ and 50 μ) attached

horizontally to the edge of the hole).

- C_2H_2 gas puffing in front of a disc target with a 1mm or 2mm hole in the center.
- Measurements of line intensities in transverse and axial directions.
- Measurements of level populations and estimation of gain for these different conditions (specifically, we will look for strong enhancement of CVI 182Å line in axial direction with search for possibilities to obtain lasing action on this transition).
- Analyze the results of experiments using the computer code which we will develop.

(h) Conduct 4 month experiment with gas targets to look for maximum population inversions in Hydrogen-like CVI and Lithium-like CIV, OVI and NeVIII.

- C_2H_2 , CO_2 , O_2 , Ne gas targets over a range of pressures and additions of Ar or Xe for faster cooling were to be studied.
- Measurements of line intensities in transverse and axial directions.
- Measurements of population inversion and gain.
- Interpretation of the data using the computer code.

(i) Conduct 4 month experiment with solid targets for

maximum population inversion in Li-like FVII,
AgXI and SiXII.

- Teflon, aluminum and quartz disc targets with a 1mm hole in the center were to be used.
- Measurements of line intensities in the transverse and axial directions.
- Measurements of population inversions and gain.
- Interpretation of the data using the computer code.

(j) Conduct 3 month experiment with gas and solid targets to look for population inversion in H-like OVIII, FIX and NeX

- O₂ and Ne gas targets were to be created by puffing with a fast valve (gas to be localized in a relatively small volume just before the CO₂ laser pulse) A relatively low gas pressure is to be used to obtain a high peak plasma temperature.
- Teflon foil target with and without a 1 mm hole in the center. The thickness of target will be varied to obtain an initially high peak temperature.
- Measurements of population inversions and analysis of the data using the computer code.

Most of the tasks which were planned for the first eight

months of the first year (Fy 84) were completed. We also finished some tasks which we were planning for the end of the first year and the beginning of the next year's program as well as incorporating into the program additional investigation of gain in carbon fiber targets of diameter 20μ to 200μ . We placed significant emphasis in the last 3.5 months on this new task because initial measurements of gain for the CVI 182A line indicates that we can expect very promising results (i.e. very high gain) in the near future.

The following tasks were performed in eight months of the first year of the proposal:

- (a) A new optical system for CO_2 laser focussing consisting of two 12" diameter flat cooper mirrors (one with 3.5" hole in center) and 12" spherical cooper mirror ($f = 300$ cm focal length), all enclosed in a vacuum chamber, was designed, built and installed. This new optics enables the CO_2 laser beam to be focussed to a spot of dimension $100\mu \times 200\mu$ which is a very significant improvement in comparison to the old optics with NaCl lens (12" diameter, $f = 300$ cm). In this way, the focussed CO_2 laser power density is increased by an order of magnitude.
- (b) Optimization of gas mixture in the CO_2 laser units

for minimization of laser beam "tail." This provided us with a satisfactory pumping laser beam for the first year tasks. Investigation of "plasma shutters" (reflection by the plasma of a portion of the CO_2 laser intensity during pulse decay) indicates that naturally occurring shutters should play a positive role in shortening the laser pulse. Work on application of the saturable absorber SF_6 for development of shorter, more "clean" CO_2 laser pulses is planned for the second year program for use in experiments with the higher-Z ions AgXI , SiXII (Li-like) and OVIII ; FIX and NeX (H-like).

- (c) Work on development and application of a gas jet-stream for creation of a localized high pressure gas target is in progress and is expected to be finished before the end of Fy 84. This type of gas target will be important for NeVIII gain measurements at 292Å.
- (d) We developed and tested a number of carbon targets: carbon discs with 0.5, 1.0 and 1.5 mm holes in the center, carbon discs with a 1.5 mm hole and 4 aluminum blades, carbon blades, carbon discs with thin C-blades, and C-discs with a 1 cm long C-filament attached to the edge of 1.5 mm central

hole. We also examined the interaction of the CO₂ laser with discs consisting of teflon (to provide flourine lines), quartz (to provide silicon lines) and aluminum. All these discs had a 1.5 mm hole in center.

In addition, we developed a procedure for using carbon fiber targets. C-fibers with thicknesses from 20 to 200 μ and lengths from 2 to 20 mm (length depended on experimental purpose) have been utilized. A technique for fine alignment of the CO₂ laser beam on these fibers was developed and successfully applied.

- (e) Modification of axial EUV monochromator and transverse EUV duochromator for time resolved measurements and calibration of both of these instruments for wavelengths and absolute intensities. This task has special significance from the point of view of population inversion and gain measurements. We dedicated the first 2.5 months (from November 83 till middle of January 84) to this task. We installed 2 channeltron multipliers in the EUV duochromator and a 20 stage electron-multiplier in the axial EUV monochromator. After intensive work on eliminating noise problems in the detection system and obtaining

a good S/N ratio, we provided careful wavelength calibrations for both EUV instruments.

Absolute intensity calibration of duochromator was initially performed on the Princeton Large Torus (PLT) tokamak by comparing line intensities with those measured simultaneously by another EUV spectrometer, which was calibrated using synchrotron radiation.

Final absolute intensity calibrations of transverse and axial EUV instruments were performed on our system in situ by the branching ratio method at wavelengths of 150Å and 88Å. In addition, relative sensitivities of the transverse and axial instruments were measured by comparing line intensities using a vertical carbon fiber target (both instruments see the same plasma - more details are presented in attached papers).

- (f) Initial stages of computer code modification for hydrogen-like ions are finished. Further modifications of the code (including additional radiation cooling by Ag-ions) are in progress.
- (g) After the axial and transverse EUV instruments were calibrated [task (e)] we performed intensive experiments with carbon discs with different size

holes in center (0.5, 1.0, 1.5 and 2.0 mm). The best results were obtained for a C-disc with 1.5 mm hole and with magnetic field $B = 90$ kG (maximum magnetic field used). In this experiment we measured very significant enhancement of CVI 182A line intensity in axial direction, which corresponds to a one pass gain $G = k \cdot q = 3.5$. Slightly lower gain was measured for C-disc with four A_2 -blades (1.5 mm hole). Probably the A_2 -blades provided intensive cooling in the initial stage of plasma development (which resulted in too low initial temperature), so we did not observe (as expected from computer calculations) improvement of the gain. Changes in target design should improve the gain. Experiments with a C-filament or C-blade attached to the C-disc did not indicate any improvement in gain. However, the CO_2 laser beam interaction with an isolated C-blade creates a plasma with small diameter and hence with large population density, as radial profile measurements showed. These last results stimulated our experiments with C-fibers. In one of our initial experiments (still without magnetic field), using a 75μ diameter x 4 mm long C-fiber, we observed very encouraging gain $G = 2.8$. Fibers with larger or smaller diameter have not given us such gain as yet. Experiments with longer fibers and with

magnetic field are in the process of preparation. (To carry out experiments with the magnetic field we have to ensure that magnet stresses will not be transferred to the fiber.)

We also measured population inversions in Li-like OVI and NeVIII ions. For NeVIII we obtained a good relation between population inversion and initial neon pressure. Experiments using a shorter neon column but with higher pressure are in the final stages of preparation.

In summary, in the Report we presented results of work for the first year (Fy 84) of AFOSR support of X-ray laser experiment in PPPL, namely:

- (a) We built a new optical system for the CO₂ laser which allowed us to obtain an order of magnitude higher power density in the focal plane in comparison to the old optical system.
- (b) We improved the time evolution of the laser pulse.
- (c) Work on the jet-stream gas target is progressing well.
- (d) A number of carbon targets were developed and

tested. In addition, we started intensive work preparing for a series of experiments with thin carbon fibers.

(e) EUV axial and transverse instruments were modified for measurements of line intensities as a function of time. Instruments were calibrated for wavelengths and absolute intensities.

(f) First stage of computer code modification was performed.

(g) We measured single pass gains:

- $G = k \cdot l = 3.5$ for carbon disc with 1.5 mm hole in center in magnetic field $B = 90$ kG.
- $G = 3.0$ for carbon disc with four Ag-blades ($B = 90$ kG).
- $G = 2.8$ for a 75μ diameter x 4 mm long carbon fiber (initial experiments, no magnetic field applied yet - very promising result).

We measured also population inversions in NeVIII as a function of initial gas pressure.

More detailed information about some of the above results is presented in the attached three papers.

IV: APPENDIX A

Papers presented in Conference on EUV Lasers

1. Recent Experiments on Soft X-Ray Laser Development
in a Confined Plasma Column
2. Spatial Profiles and Time Evolution of Plasmas Which
Are Candidates for a Soft X-Ray Laser
3. Soft X-Ray Spectra, Population Inversions and Gains
in a Recombining Plasma Column

RECENT EXPERIMENTS ON SOFT X-RAY LASER DEVELOPMENT IN A CONFINED PLASMA COLUMN

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ABSTRACT

We present studies of magnetically confined and expanding recombining plasma columns and measurements of gain for hydrogen-like (CVI) ions and population inversion for Li-like (NeVIII) ions.

I. INTRODUCTION

Extensive research on x-ray laser development has provided a number of interesting results for different schemes, e.g. recombination¹⁻⁴, line-coincidence⁵⁻⁷, photo-pumping^{8,9} and very recently multi-photon ionization schemes.¹⁰ Each of these approaches has certain advantages and disadvantages. For example, recombination schemes which are one of the most promising approaches for soft X-ray laser development, require very fast plasma cooling and, at the same time, uniform conditions in the direction of the expected lasing action. To help solve this problem, we proposed to use a plasma column confined by a strong solenoidal magnetic field and cooled by radiation losses.¹¹

We have shown experimentally¹² that radiation cooling of a magnetically confined plasma column can be more efficient than adiabatic cooling of a freely expanding plasma. The magnetic field prevents the radius of the column from increasing and hence prevents a rapidly decreasing electron density. The plasma was created by the interaction of a 1 kJoule (10 - 20 GW) CO₂ laser with a solid or gas target. Time integrated spectra in the EUV recorded simultaneously in the axial and transverse directions indicated an enhancement of CVI 182Å line intensity in the axial direction, and population inversion for Li-like CIV, OVI, FVII and NeVIII ions¹².

In this paper we present an overview of our recent time resolved measurements in the EUV of H-like CVI, and Li-like NeVIII line intensities spatial distributions, levels populations, and population inversions, as well as gain measurements for the CVI 182Å line. More detailed information about the time evolution and spatial distributions of EUV line intensities are presented in the next paper¹³ of this proceedings, and on population inversions and gain measurements in the subsequent paper¹⁴.

II. EXPERIMENTAL ARRANGEMENT

The experimental set-up is presented in Fig. 1. This differs from the one presented previously¹² in the focusing system of the

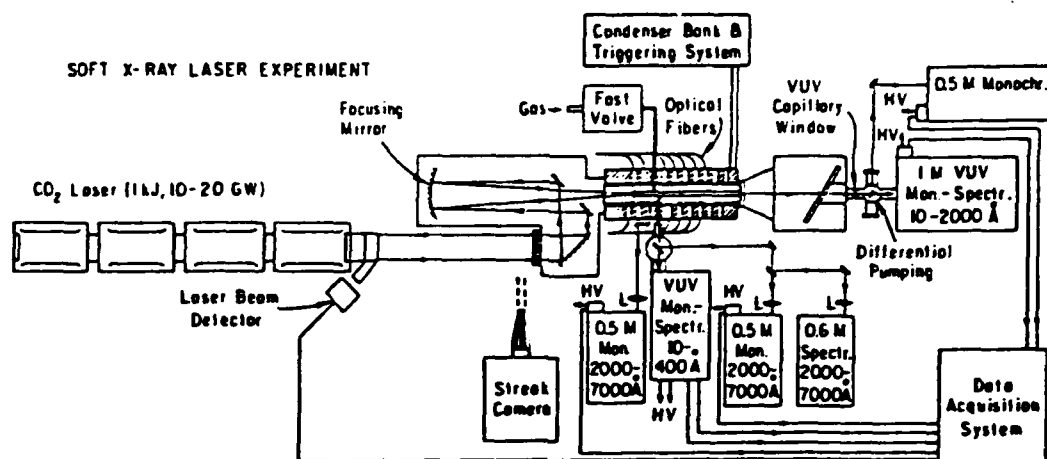


Fig. 1 Schematic of experimental arrangement.

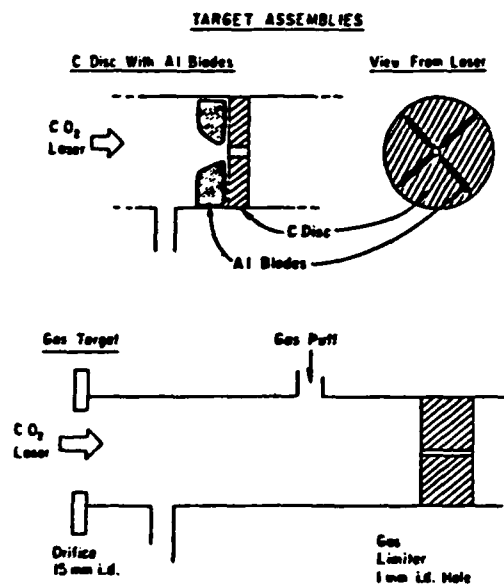


Fig. 2. Carbon-disc target with four Al-blades (a) and gas target (b) assemblies.

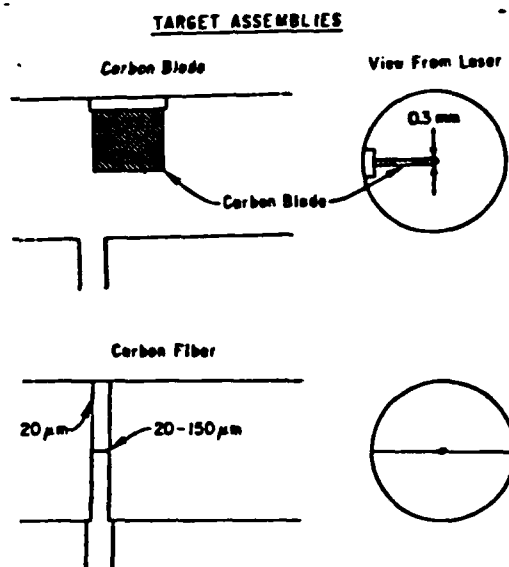


Fig. 3. Carbon-blade (a) and carbon-fiber (b)

CO₂ laser. Presently we are using a spherical mirror instead of a NaCl lens to focus the laser beam. This enables us to significantly decrease the focal spot size from 1 mm in diameter to an ellipse of 0.2 mm x 0.4 mm. In this way the intensity of laser beam in the focus is increased up to 10^{13} W/cm². The optical arrangement for the diagnostic instruments, except for 0.6m spectrometer, was the same as in the earlier work.¹² However, presently we are using a larger variety of targets. In addition to gas targets (CO₂, O₂, Ne) we have performed experiments with solid targets [C (carbon) - disc, C-disc with Al-blades, C-blade, C-fiber; teflon disc, quartz disc]. All the discs targets presented here had a 1mm or 1.5 mm hole in the center, with the laser beam focused on the edge of the hole. Our attention to solid targets was motivated by experimental conditions: with solid targets we expected to more easily obtain an electron density close to the critical density for the CO₂ laser wavelength of 10 μ ($n_e(\text{cr}) = 10^{19}$ cm⁻³) than for gas targets. The gas targets provided us with a longer and more uniform plasma column, however with the present gas puffing system it was difficult to maintain a high gas pressure in a short windowless column.

In the upper part of Fig. 2 is shown a carbon disc (1.5 mm hole in center) with 4 aluminum blades. In the lower part is shown the schematic arrangement for the gas target. Carbon blade and carbon fiber assemblies (horizontal plane) are shown in Fig. 3. The CO₂ laser is located on the left hand side, axial monochromators on the right hand side and transverse instruments are on the bottom of Fig. 3. A EUV grazing incidence duochromator (transverse instrument) and monochromator (axial instrument), each one operating in the spectral range 10-350Å, were equipped with two channel electron multipliers and a 16 stage electron multiplier, respectively. These detectors were installed after the spectra produced by the carbon disc were obtained with the new focusing optics for CO₂ laser.

The rise time of the axial instrument was $\Delta t = 20$ nsec and approximately twice shorter for the transverse one. Both instruments were calibrated for absolute intensity at 150Å and 88Å by the branching ratio method.^{15,16} This calibration is still in a preliminary stage and more measurements are required¹³ (by using vacuum spark-gap). The instruments were also calibrated for relative intensity at 182Å and 28Å using the known line intensity ratio 182Å (3-2) / 28Å (3-1) in a relatively low density plasma (plasma optically thin for these transitions, no line intensity enhancement). The relative sensitivity of the axial and transverse instruments was obtained for the CVI 182Å and CVI 33Å lines by viewing simultaneously with both instruments the plasma created by the CO₂ laser interaction with a vertical fiber,¹⁴ similarly to the Hull University experiment.² For a laser created plasma the last method we considered as more reliable than branching ratio method for the comparison of the sensitivity of the axial and transverse monochromators.

III. RESULTS

With the new focusing optics for the CO_2 laser we attempted to significantly increase the axial intensity of the CVI 182Å line in comparison to the CVI 33.7Å line using the same target (carbon disc with 1 mm hole in center), magnetic field ($B = 50$ kG), and spectrometers as in our earlier work.¹² We present in Fig. 4 a densitogram of a spectral plate in the vicinity of the 182Å and 33Å lines, obtained with the axial EUV spectrometer (the sensitivity of the spectrometer near 33Å was significantly lower than for 182Å, however the relative sensitivity for both wavelengths was the same as in Ref. 12). The intensity ratios of the CVI 182Å and CVI 33.7Å lines as well as the 182Å line and neighboring lines (particularly OVI 173 Å line) increased by a factor of 2-3 in comparison to our earlier data.¹²

Most of the measurements of line intensities presented here and in the next two papers^{13,14} were performed with time resolution. Time resolved measurements provided us with much better information on level populations and intensity enhancements (gains) than the time integrated spectra. It is also important that from the time resolved measurements we have information from one discharge whereas for a spectral plate exposure we needed several discharges.

The time evolution of the CVI 182Å and CVI 135Å (4-2 transition) line intensities, measured in the axial and transverse directions are presented in Fig. 5 for two consecutive discharges. In the upper part of the figure the laser intensities

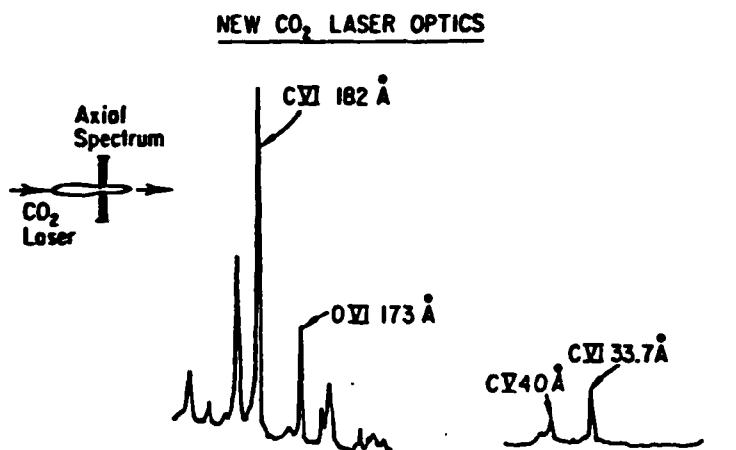


Fig. 4. Axial emission spectra in the vicinity of CVI 182Å and CVI 33Å lines.

obtained with a photon drag detector are shown as a function of time. The laser power was similar for both shots with the laser energy in the range of ~ 500 J. The plasma column was created in a solenoidal magnetic field $B = 90$ kG by focusing the laser beam onto the edge of the 1.5 mm hole in the center of the carbon disc. One channel of the transverse EUV duochromator recorded the CVI 33.7Å line and showed very good reproducibility of CVI radiation.

The second channel of the EUV duochromator and axial EUV monochromator, both measured simultaneously the intensities of the CVI 182Å line for first shot (first row in Fig. 5) and CVI 135Å line for the second shot (second row in Fig. 5). The relative intensity of the CVI 135Å line in the transverse direction was obtained by subtracting the known contribution of the fourth order of the 33.7Å line, which was less than 30% of total intensity at 135Å (for the axial instrument this contribution is negligibly small due to the different angle of blaze of the grating). We had found that the ratio of axial to transverse intensity of the CVI 182Å line exceeded the same ratio of the CVI 135Å line by a factor larger than 10. Such enhancement of axial intensity of CVI 182Å line corresponds to a one pass gain $k.l = 3.5$.

The applied magnetic field plays a positive role in the generation of high 182Å line intensities. We observed that for magnetic field $B = 90$ kG the CVI emission in the transverse direction increased by up to factor of 5 and shows a faster decay¹³ consistent with fast radiation cooling in the confined plasma column.

We have performed a number of experiments using aluminum blades attached to a carbon disc with a 1.5 mm hole in the center (Fig. 2). We expected to increase the CVI 182Å line enhancement in comparison to the enhancement obtained for the C-disc without Al-blades. Such an expectation follows from the computer calculation of effectiveness of medium Z elements (Al in this case) in cooling a transient high density plasma by radiation losses (Fig 6). A coupled set of rate equations for either carbon or carbon with aluminum is solved in time self consistently with a set of energy equations which describe the electron temperature. The peak value of the laser power is chosen to yield the same peak electron temperature for both cases; it is about 2.8 times greater for the carbon and aluminum system than for the case with carbon alone. In both instances the total number of ions is $4.5 \times 10^{17} \text{ cm}^{-3}$ and the electron density is approximately $2-3 \times 10^{18} \text{ cm}^{-3}$.

One may see from Fig. 6 that aluminum plays a significant role in the process of faster radiation cooling for electron temperature, T_e , below 100 eV. Aluminum is especially important for plasma cooling below 20-30 eV. Experimentally we observed higher CVI 182Å line intensity in the spectra and a faster decay time of the CVI line intensities. However, enhancement of the CVI 182Å line intensity did not differ substantially from the one with plain C-disc. One possible explanation may be an improper concentration of Al in the carbon plasma.

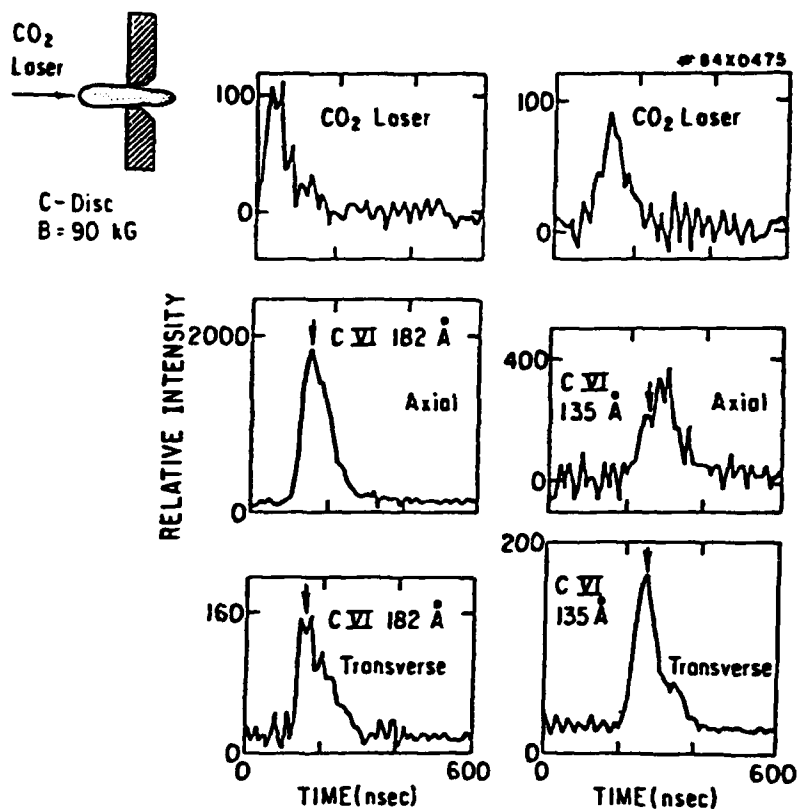


Fig. 5. Time evolution of C VI 182 Å and C VI 135 Å line intensities, measured in the axial and transverse directions, indicating gain-length product $k \cdot l \approx 3.5$.

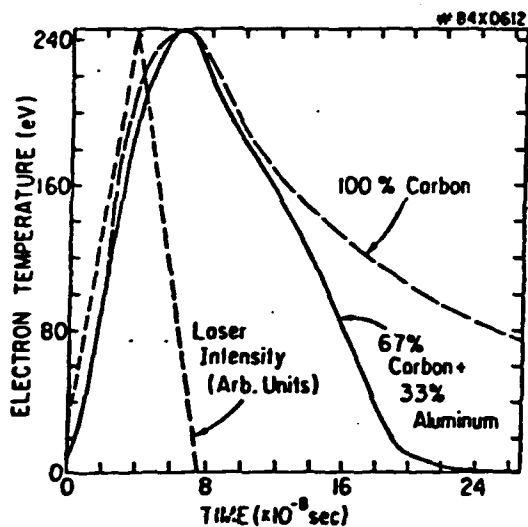


Fig. 6. Computer calculations of effectiveness of radiation cooling for carbon and carbon-aluminum plasmas.

The radial distribution of the CVI line intensities shows much narrower profiles when the CO₂ laser beam interacts with a smaller target (e.g. carbon blade) than with a disc target, in agreement with the observations of Crawford and Hoffman.¹⁷ With the CO₂ laser (energy ~ 120J) focused on the corner of the carbon blade, the measured radial profile of the CVI 182Å line emission was smaller than 0.3 mm, indicating that the total population of level $n = 3$ is $N_3 > 10^{14} \text{ cm}^{-3}$ for this relatively low laser energy (for more details see following paper¹³).

A few preliminary experiments were conducted with carbon fibers (Fig. 3) located on the axis of the CO₂ laser beam. In contrast to the Hull University experiment,² we used fibers with a much larger diameter. The diameter of the fibers varied from 60 μ to 200 μ and the length from 2 mm to 10 mm. Up to now the most promising result was obtained with a 75 μ x 4 mm fiber, which was completely in view of both the axial and transverse EUV instruments. The measured enhancement of 5.3 of the 182Å line in the axial direction corresponds to a one pass gain $k.l = 2.8$ (Ref 14). In this preliminary experiment we had not yet used the magnetic field, which seems to be particularly suitable for thinner fibers (20-60 μ) for stabilization purposes. An estimation of the carbon ion density in the plasma column indicates that the core of the fiber remains cold and plays the role of a source of particles as well as a heat sink, providing extra cooling in addition to radiation cooling.

Our earlier¹² works on population inversions in Li-like CIV, OVI, FVIII and NeVII ions were continued in more recent experiments with time resolution. In Fig. 7 are shown changes in the population inversion of the 4d and 3d levels of NeVIII as a function of initial neon (Ne) pressure.

Neon gas was puffed into the target chamber a few milliseconds before the laser pulse and was limited to a region 5 cm long by mechanical apertures. The initial Ne pressure was controlled by varying the delay of laser pulse with respect to the gas valve opening. The populations of the 4d and 3d levels were obtained from measurements of the intensities of the NeVIII 73.5Å (4d-2p transition) and NeVIII 98.2Å (3d-2p transition) lines in the transverse direction with the EUV duochromator. Column density populations were deduced from the absolute intensity.

Since these lines are close in wavelength corrections for the variation of instrument sensitivity as a function of wavelength is small and was neglected. Hence the relative population of the 4d and 3d levels can be much more accurately determined than the absolute populations, which depend on the reliability of the absolute intensity calibration. It can be seen that the 4d population exceeds the 3d population for higher pressure with the maximum population inversion at a gas pressure $p = 12-15$ torr. Since the 4d and 4f levels are expected to be closely coupled by collisions this leads to gain on the 4f-3d transition at 292Å. The effect of optical trapping on the observed 73Å / 98Å ratio was checked by measuring the ratio of the intensity of the fine

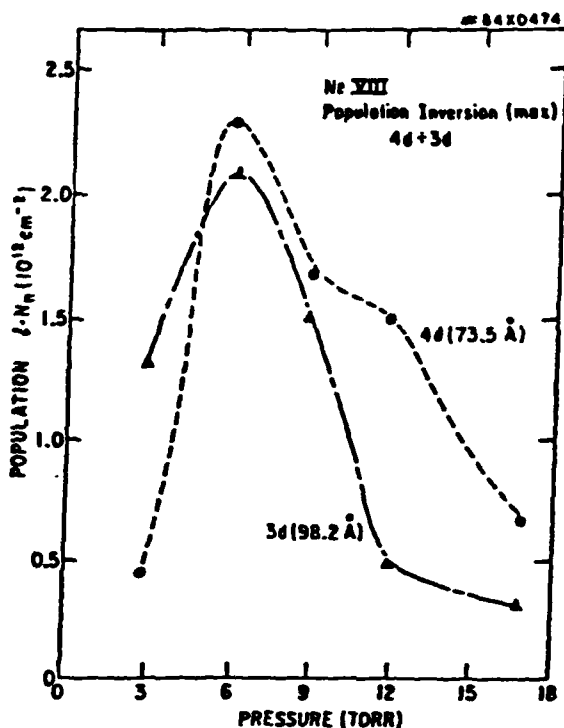


Fig. 7.
Population
inversion of the
4d and 3d levels
of NeVIII as a
function of
initial neon
pressure.

structure components of the 98Å line. This was close to the theoretical value for an optically thin plasma.¹⁴ We also observed the NeVIII 292Å line emission in the axial direction but did not observe a significant increase at high neon pressures, possibly due to absorption in the neutral gas boundary. Further target development should help this problem.

IV. CONCLUSIONS

Enhancement of the CVI 182Å line intensity in the axial direction was measured for C-disc plasmas in a magnetic field $B = 90\text{kG}$, indicating a gain \times length product $k \cdot l = 3.5$ for CO_2 laser energy $\sim 500\text{--}600$ Joules.

A few preliminary experiments with carbon fibers showed promising results for CVI 182Å line: gain \times length ~ 3 for $75 \mu \times 4 \text{ mm}$ fiber. The application of the magnetic field and a thin aluminum coating of the fiber for faster radiation cooling is expected to improve gain.

Population inversions of the 4d and 3d levels of Li-like NeVIII were reported as a function of Ne gas pressure. The line of the potential lasing transition NeVIII 292Å was monitored, however an enhancement in the axial direction was not yet observed. This may be due to absorption of 292Å line in Ne gas on the path between the plasma and the monochromator and/or the population density of the

4f level was too low. New gas target designs should help solve this problem.

ACKNOWLEDGMENTS

The authors are thankful to H. Furth for helpful discussions and encouragement. Productive discussions with J.L. Schwob and his help in operating EUV duochromator is highly appreciated. The authors would like also thank D. DiCicco and V. Vasilotas for technical assistance.

The earlier stage of this work was supported by DOE Basic Energy Sciences, and recently is supported by U.S. Air Force Office of Research, Contract No. AFOSR-84-0025.

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SPATIAL PROFILES AND TIME EVOLUTION OF PLASMAS
WHICH ARE CANDIDATES FOR A SOFT X-RAY LASER

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ABSTRACT

We present spatially resolved measurements of EUV line intensities and excited state populations in plasmas produced by the interaction of a CO₂ laser with carbon and aluminum targets of differing configurations. The results are assessed in terms of conditions necessary for a soft X-ray laser.

I. INTRODUCTION

The quest for laser action in the soft X-ray region poses a severe technical challenge, not only in achieving a high population inversion at a single point in space, but also in creating an extended medium of appropriate length, width and spatial uniformity to generate sufficient gain for a practical laser. In the previous paper¹ our experiment on soft X-ray laser development was introduced. This paper presents data from the experiment focussing on spatially resolved CVI line emission and populations in the light of the following requirements for a practical recombination laser. First, the effective length of the plasma should be sufficient for a gain-length product of 10 or more. Second, the plasma width must be low enough to avoid optical trapping on the radiative decay from the lower level of the potential lasing transition. Third, the upper level population of the potential lasing transition ($n = 3$ for CVI 182Å) should be high enough for significant gain. A unique feature of our experiment is the use of a magnetic field to maintain a high electron density conducive to fast recombination. We present data showing the effect of the magnetic field on the spatial distribution and time evolution of the plasma. Other studies of CO₂ laser produced plasmas in magnetic fields have been done by Crawford and Hoffman,² and Loter et al.³

II. EXPERIMENTAL SET UP

A 1 kJ CO₂ laser was used to create a plasma from a variety of targets (see Fig. 1 and also the previous paper).¹ A EUV grazing incidence duochromator, equipped with two channel electron multipliers, observed plasma emission in the radial direction. A scanning slit assembly limited the field of view of the duochromator to a region 4 mm x 0.16 mm, the long dimension being parallel to the laser beam. By scanning the slit the transverse distributions of the line intensities were built up on a shot to

shot basis. Between runs the target and laser focus were moved to different axial locations and hence a complete spatial picture of the plasma was constructed. A grazing incidence monochromator equipped with a 16 stage electron multiplier (rise time 20 nS) also

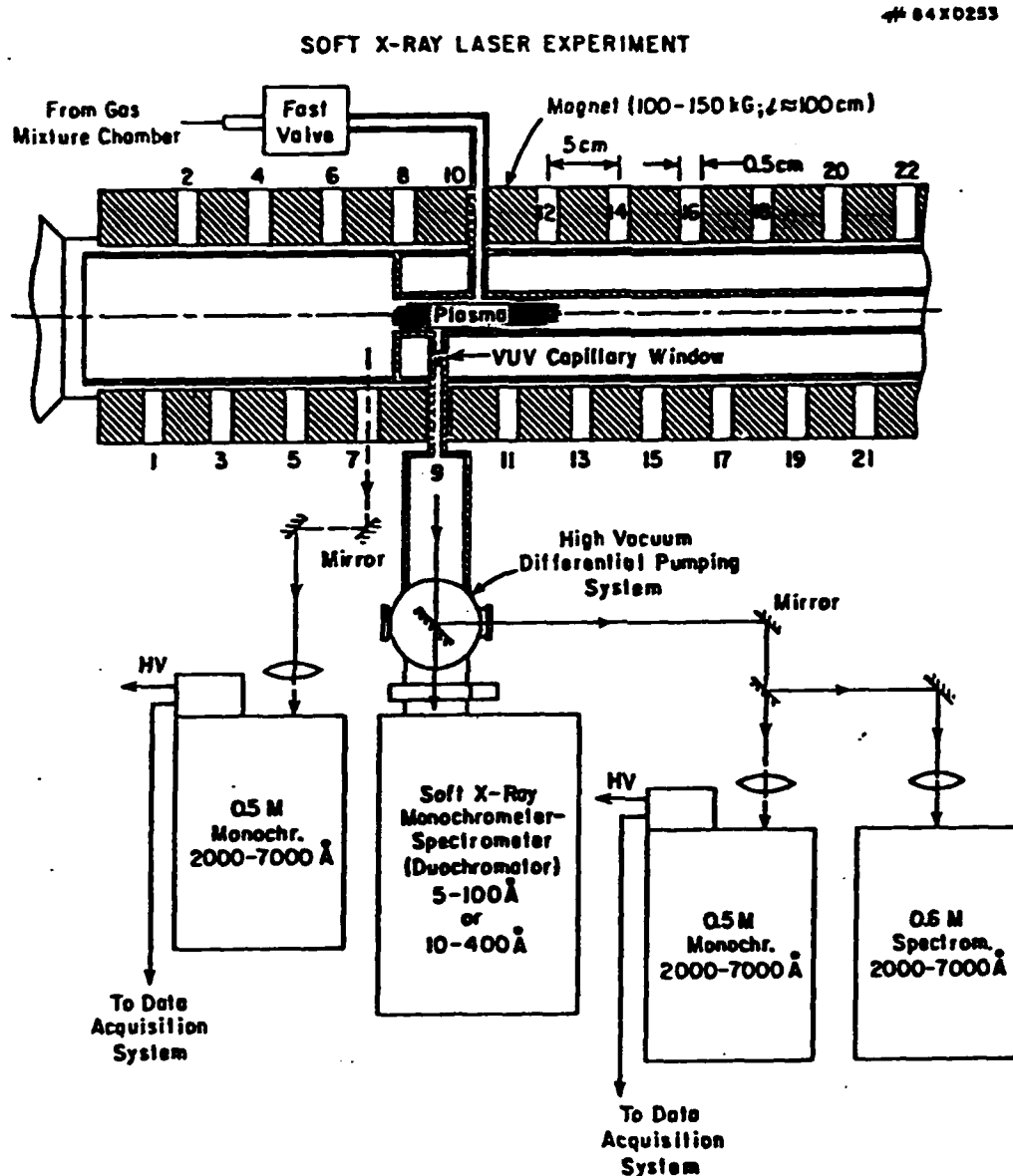


Fig. 1. Experimental arrangement of transverse spectroscopic instruments showing arrangement of beam splitters used in absolute intensity calibration.

observed the plasma emission in the axial direction. A grazing incidence mirror⁴ was used to image the plasma on the monochromator entrance slit. The emission in the axial and transverse directions was simultaneously observed by two absolute intensity calibrated air monochromators using beam splitters so that each pair of EUV and air instruments observed practically the same region of the plasma. In this way it was possible to use the branching ratio method^{5,6} to provide an in-situ absolute intensity calibration for the VUV instruments. The line pairs used were OVI 150Å/3811Å and NeVIII 88Å/2820Å.

III. RESULTS

A. CARBON DISC WITH FOUR ALUMINUM BLADES

This target consists of a carbon disc with a 1.5 mm hole at the center to permit axial observations of the plasma. Four aluminum blades were arranged on the target surface to mix aluminum with the carbon plasma to provide additional radiation cooling (see Fig. 2 in the previous paper).¹ Figure 2 shows radially resolved measurements of the CVI 33Å (1-2 transition) and CVI 182Å (3-2 transition) line intensities taken at three different axial locations from the target surface. The CO₂ laser energy was 70-90 J and a magnetic field of $B = 50$ kG was present. The plasma appears to be moving axially and the line intensities at this transverse location decreased by a factor of two from 1 to 11 mm from the target surface. The difference between the 33Å and 182Å time histories is an instrumental effect currently under investigation. It does not affect the timing of the signals at 1, 11 and 22mm.

Figure 3 shows time integrated profiles of the CVI 33Å and CVI 182Å line intensity from the same experimental run as Fig. 2. The signals are time integrated to avoid the instrumental difference in time histories but in fact a plot of the peak signals is similar. In general the CVI emission extends over a diameter of 1 mm or more. Data taken with a higher laser energy shows a larger diameter. A width of 1 mm or more may put a severe limit of the CVI ground state population in order to avoid optical trapping of the CVI 33.7Å radiation, unless the population of the lower level of the potential lasing transition (3-2) can be reduced (e.g., by fast transport).

The data indicates there are large "wings" in the spatial profile of the CO₂ laser focal spot which are responsible for the large plasma width and the next section will describe a carbon blade target designed to overcome this problem. The maximum CVI $n=3$ level population for this low energy of the CO₂ laser is $7 \times 10^{13} \text{ cm}^{-3}$ close to the target, based on an overall plasma width of 1 mm. For a laser energy of ~ 600 J the column density ($N_3 \cdot l$) is significantly higher, but still insufficient for laser action. However, as with all absolute intensity calibrations even though the greatest care was taken with the measurements it was never possible to completely rule out unidentified systematic effects.

The actual population could be higher. A second intensity calibration based on a vacuum spark source is currently underway. Figure 4 shows the effect of a 90 kG magnetic field on the CVI 33Å and 182Å line emissions. For the 90 kG case the CVI emission increased by up to a factor of five and shows a faster decay consistent with fast radiation cooling in the confined plasma column.

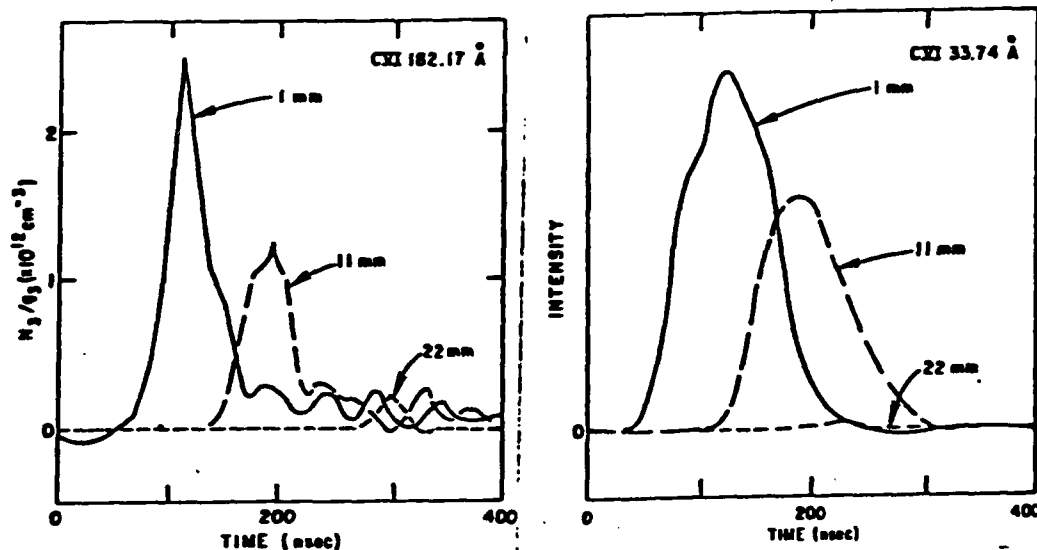


Fig. 2. CVI 182Å and 33Å emission at three axial locations: 1, 11 and 22 mm from the target surface. The radial location corresponds to + 0.7 mm in Fig. 3.

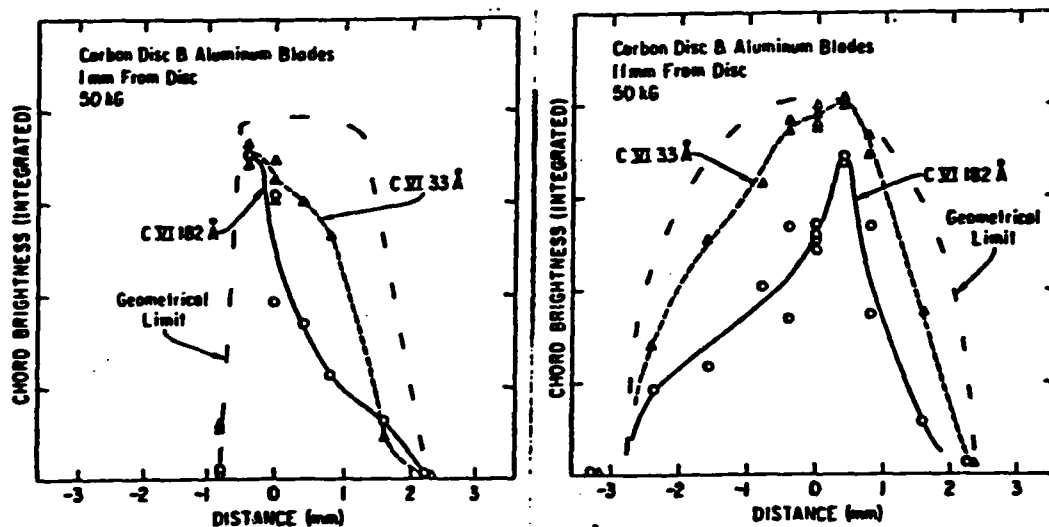


Fig. 3. Transverse scan of CVI 182Å and 33Å 1 and 11 mm from the disc. The outer dashed line represents, at 1 mm, the area not obstructed by the aluminum blades and at 11 mm, is a semi-ellipse representing the geometrical limit of the circular feedthrough. The line through the data points are intended as a visual aid.

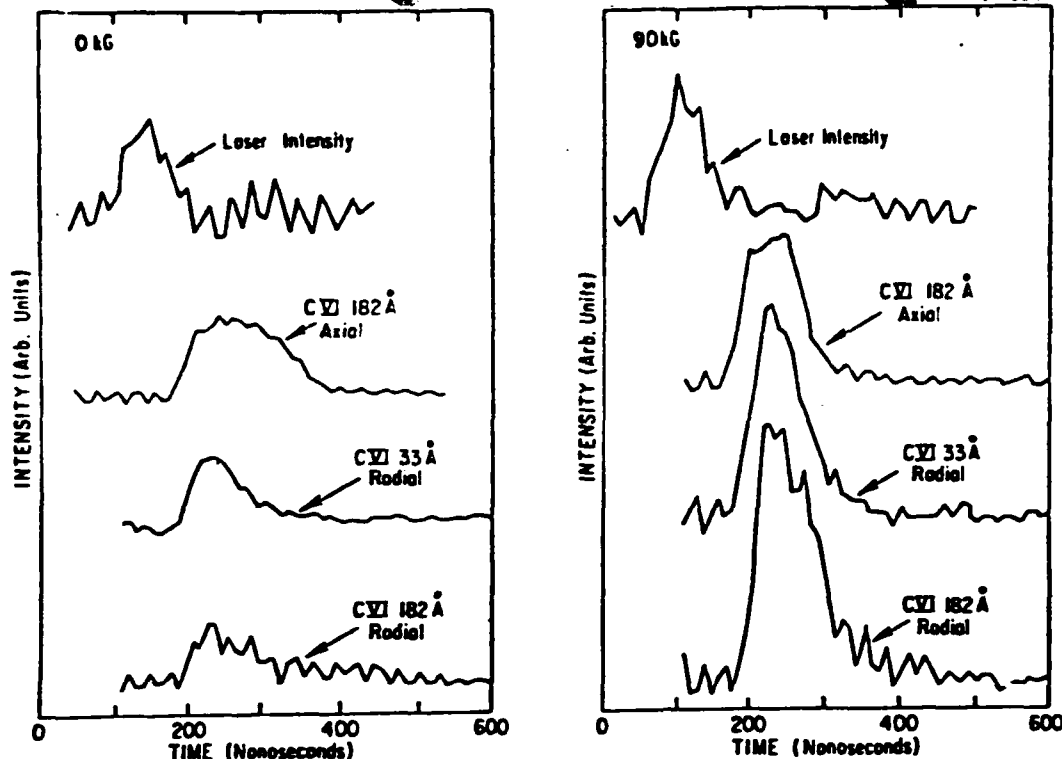


Fig. 4. Time resolved CVI line intensity measurements in axial and transverse directions taken with and without a magnetic field of $B = 90$ kG. The target was a carbon disc with 4 aluminum blades. The radial data was taken 1 mm from the target surface and laser energy was 460 J ($B = 0$ kG) and 610 J. This figure has not been adjusted for the intrinsic delay of ~ 60 -80 ns in our EUV detectors.

B. CARBON BLADE TARGET

This consists of a 0.3 mm thick carbon blade placed horizontally in the target chamber with the CO_2 laser focussed on the corner of the blade (see Fig. 3 in previous paper).¹ The idea here is that the low intensity wings in the laser focal spot do not interact with the target and hence the transverse profiles in the vertical direction are narrower than in the case of the carbon disc. This is borne out in the data of Fig. 5. The width at half maximum for CVI 182 Å is 0.4 mm and, surprisingly for the $B = 0$ kG case is even narrower being limited by the instrumental resolution for this data of 0.3 mm. This is encouraging both for carbon blade plasmas and also by implication for the carbon fibre plasmas discussed in the next paper.⁷ The spatial profile of the CVI 33 Å emission appears to be broader than the CVI 182 Å emission. In the horizontal direction the plasma thickness is estimated to be in the range 0.2 - 0.8 mm. In Fig. 5 the maximum population of level $n=3$ of CVI is $5 \times 10^{13} \text{ cm}^{-3}$ for the $B = 50$ kG case and $2 \times 10^{14} \text{ cm}^{-3}$

for the $B = 0$ kG case, based on a plasma thickness of 0.2 mm, for a relatively low laser energy of ~ 120 J. Initial results with 600 J laser energy show an order of magnitude higher column density at $B = 50$ kG. These numbers are encouraging and are approaching that required for lasing action. A spatial scan at 11 mm axial distance from the target showed N_3 populations reduced by more than an order of magnitude so that at present the carbon blade plasma is clearly of very limited axial length. Further target development is necessary to combine the high CVI N_3 population and narrow width of the carbon blade plasma with the longer axial extent of the carbon disc plasma.

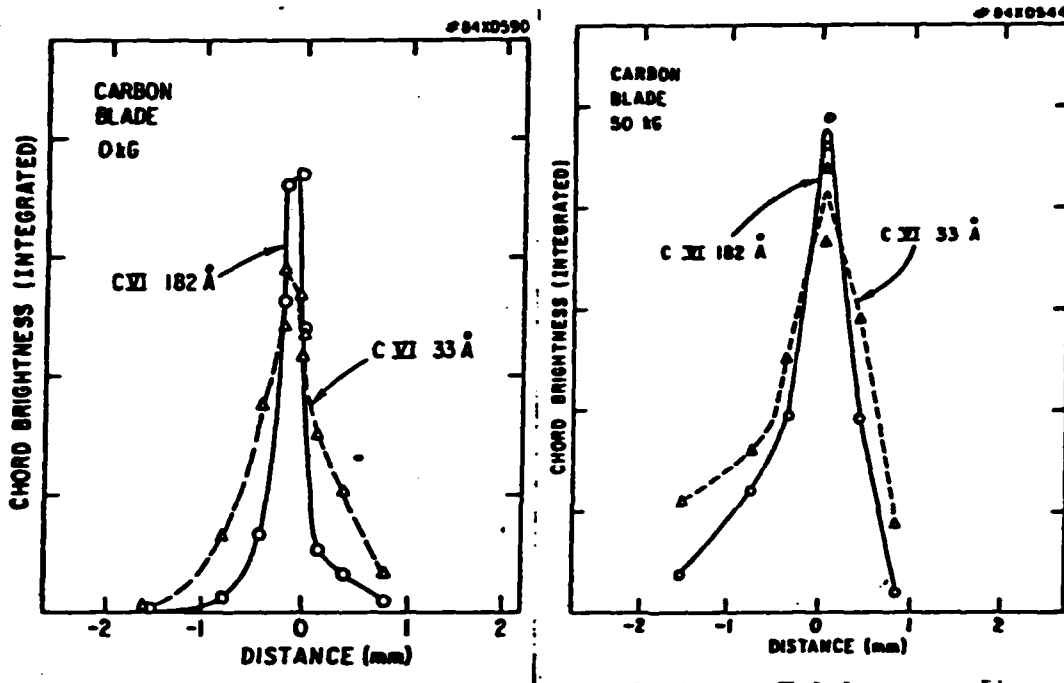


Fig. 5. Vertical distribution of CVI 182 Å and 33 Å line emissions with $B = 0$ and 50 kG showing very narrow profiles at $B = 0$ kG. The laser energy used here was 120 J.

CONCLUSIONS

We have investigated the spatial characteristics and excited state populations of plasmas produced by the interaction of a CO_2 laser with carbon and aluminum targets. The populations and geometry show promise but further target development is necessary to generate a long, narrow plasma suitable for a soft X-ray laser.

ACKNOWLEDGEMENTS

The authors would like to thank J.L. Schwob for productive discussions and help in the operation of the VUV duochromator.

They also thank D. DiCicco and V. Vasilotas for helpful technical assistance in the experiment. This work is supported by the United States Air Force Office of Research, Contract No. AFOSR-84-0025.

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SOFT X-RAY SPECTRA, POPULATION INVERSIONS
AND GAINS IN A RECOMBINING PLASMA COLUMN

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ABSTRACT

Time integrated and time resolved soft X-ray spectra have been measured from recombining CO_2 laser produced plasmas. Determinations of population inversions and gain will be discussed.

I. INTRODUCTION

In this paper, which complements the previous two, (Ref. 1, 2) we will present data showing gain and population inversions in hydrogenic carbon, CVI, and the Li-like ions CIV, OVI, FVII and NeVIII.

Prior to converting our EUV instruments (described in Ref. 1, 2) for time resolved measurements of the emission from various targets, spectra were recorded on photographic plates (Kodak #101). For proper exposure of these plates, between 5 and 15 shots were required.

These spectra were studied to (a) estimate the relative concentrations of the ion species present in the plasmas for different CO_2 laser powers and target conditions, (b) obtain time averaged estimates of plasma temperatures and densities via recombination continua, dielectronic satellites and Stark broadening, and (c) identify line ratios indicative of population inversions and gain in selected species.

Conditions were found such that emissions from the potential lasing species (CVI, CIV, OVI, FVII, NeVIII) dominated the plasma emission. Time averaged electron temperatures during the recombination phase ($T_e < 40$ eV, from recombination continua) and densities ($n_e > 10^{18} \text{ cm}^{-3}$, from Stark broadening) were consistent with conditions required for population inversions and gain³ ($T_e \leq 20$ eV, $n_e \sim 10^{18} - 10^{19} \text{ cm}^{-3}$).

II. RESULTS

A. H-LIKE CVI ION

Spectra of carbon plasmas produced from carbon (C)-discs, with and without aluminum blades (Fig. 2 in Ref. 1) were analyzed using two methods to determine the presence of enhanced axial emission of the CVI 182.17Å line (3-2 transition). First, it was found that by comparing, in the axial and transverse spectra, the 182.17Å line intensity to intensities of other CVI lines, especially 33.74Å (2-1 transition), gain-length ($k \cdot l$) products of up to 4.0 were

indicated⁴. Secondly, in the axial spectra, variations in the 182.17 to 28.47Å (3-1 transition) branching ratio were correlated with plasma conditions. Since the CVI 182Å and 28Å lines share the same upper level the ratio of the line intensities from spontaneous emission is constant under optically thin conditions. With gain on 182Å, the ratio of 182Å to 28Å line intensities should increase. The measured variation in this ratio was approximately 0.8:1 to 3.1:1. Note that the possibility of optical trapping of 28Å radiation was ruled out because the ratio of its intensity to that of CVI 26.99Å line (4-1 transition) and higher members of the CVI Lyman series remained constant to within 30% as the 3-2 to 3-1 ratio increased.

Using these methods, the highest gain was indicated in the case of carbon discs in the presence of $B = 50$ to 90 kG magnetic fields, with and without Al blades. The increase in enhancement due to the Al blades was less certain as it fell within the scatter of the enhancements estimated with the above methods.

In order to measure enhanced axial emission for the case of time resolved EUV measurements, a relative calibration of the axial and transverse EUV instruments was performed (Fig. 1). The CO₂ laser was focused on vertical graphite fibers of diameter 75-300 μ so as to produce localized plasmas seen completely by both instruments. This method of calibration has been used in the Hull University experiments⁵ with much finer fibers (< 6 μ dia.). By focusing the CO₂ laser at the fiber tips and noting that the same relative sensitivity of axial and transverse instruments was obtained within the above range of fiber diameters, it was concluded that the fibers were not blocking the view of the instruments. Measured relative sensitivities were similar at 33.74Å, 40.27Å and 182.17Å. In addition, the EUV instruments were absolute intensity calibrated using the branching ratio method (see Ref. 2).

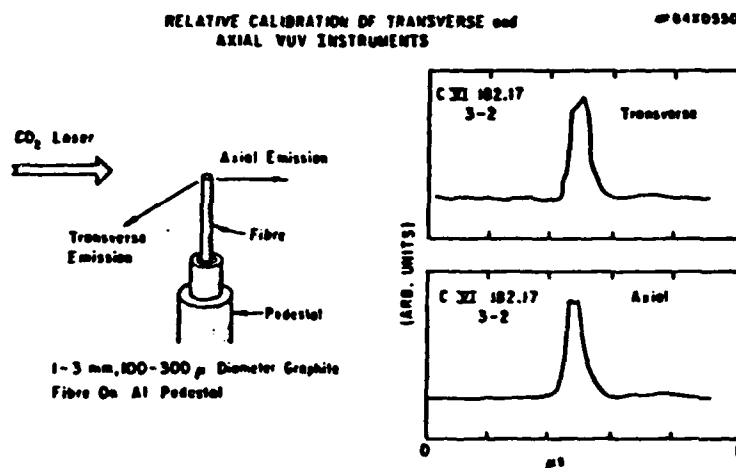


Fig. 1 Relative calibration at 182.17Å. Fiber diameter was 200 μ .

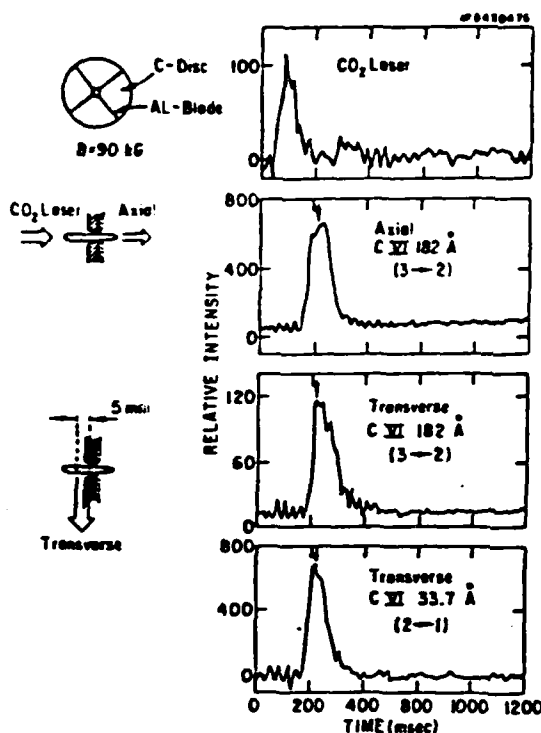
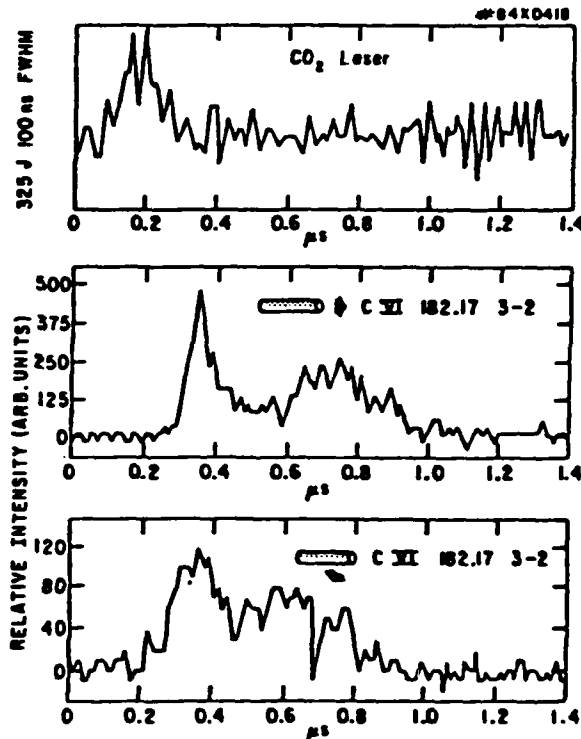
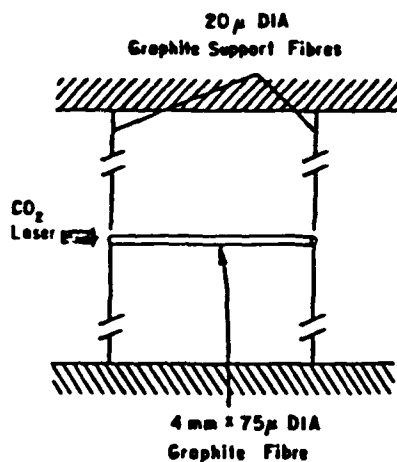


Fig. 2.
Time resolved CVI
signals for carbon
disc with Al
blades and B=90 kG
magnetic field.
Laser energy 600J.

Fig. 3.
Axial and
transverse CVI
182.17Å (3-2)
line
intensities.
Vertical scales
adjusted with
relative
calibration data.

GRAPHITE FIBRE TARGET



Time resolved CVI 33.74 and 182.17 line intensities for a C-disc (without Al blades) in a $B = 90$ kG magnetic field is presented in Ref. 1. Here, we present data for the case with Al blades (Fig. 2). The vertical scales were adjusted on the basis of the relative sensitivity determined for the axial and transverse EUV instruments. However, the geometry was such that the axial instrument could possibly view elongated plasma not seen by the transverse instrument. From radial and axial scans of 182 emission (Fig. 2, 3, Ref. 2) one can estimate for this geometry that an apparent enhancement due to plasma elongation could not be larger than approximately 2.0. Fig. 2 shows an axial to transverse enhancement (including that due to plasma elongation) of about 5.5, which is less than the enhancement of 10 for the case with no Al blades.¹

Some initial experiments were performed with long, narrow graphite fibers suspended along the axis of the magnet bore (Fig. 3, Ref. 1) and illuminated end-on with the CO_2 laser. At Hull University much narrower fibers (6 dia.) have been illuminated by a line focused laser⁵. In our experiment, thicker fibers (60 - 200 μ) were chosen in order to increase the plasma-fiber interaction. The dynamics of the laser-target interaction were not studied, and it is not known at present how far the plasma extended along the fiber length. There is evidence, (see the C-blade experiment²) however, that the plasma produced lies close to the axis defined by the fiber. This close proximity of the plasma and fiber could result in rapid cooling by neutral carbon influx and thermal conduction to the relatively cold fiber core.

The most interesting result in this set of runs was observed in the case of a 75 x 4 mm fiber (Fig. 3) which was completely in view of both axial and transverse EUV instruments. The 182 line intensities could then be compared using the measured axial-transverse relative instrumental sensitivity.

In addition to an enhancement in 182 radiation of about 5.3 ($K = 2.8$), the sharp time history of the axial 182 emission is suggestive of stimulated emission. The rise time of the axial instrument is not better than 20 ns so that possible faster time behavior has not been recorded.

B. LI-LIKE SEQUENCE RESULTS

Population inversions were measured between the 4d and 3d levels of Li-like oxygen (OVI) on the time integrated spectra recorded during initial CO_2 gas target runs. In OVI, the 4d and 4f levels are separated by .02 eV so that electron-ion collisions are expected to equalize the 4d and 4f sublevel populations. The 4f-3d transition would then be a candidate for gain. Population inversions were estimated from ratios of the 4d-2p and 3d-2p line intensities normalized by their transition rates.

These population inversions were generated over a wide range of CO_2 laser power (10^{11} - 10^{12} W/cm² for 60-80 ns FWHM and 1 mm spot diameter) and fill pressures (3-10 torr). The inversion could

TYPICAL OVI 2p-3d DOUBLET SPLITTING-TRANSVERSE

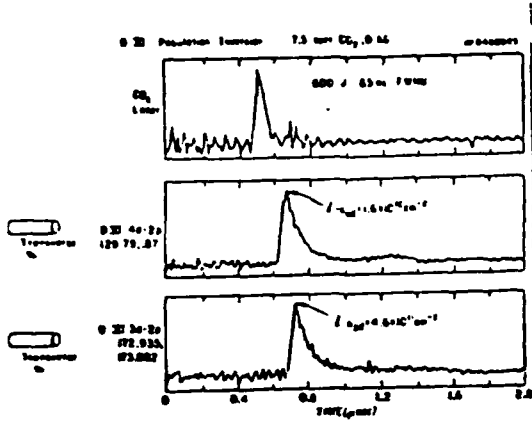


Fig. 4.
Intensities for OVI 129Å and
OVI 173Å lines for 7.5 torr
CO₂ target pressure, B=0 kG.
Column sublevel population
densities are $l \cdot n_{4d} =$
 $1.6 \times 10^{12} \text{ cm}^{-2}$ and
 $l \cdot n_{3d} = 4.6 \times 10^{11} \text{ cm}^{-2}$
($n_k = N_k/g_k$).

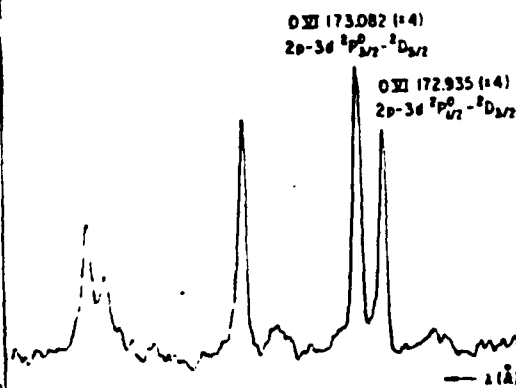


Fig. 5.
Typical OVI 3d-2p
fine structure
splitting in time
integrated spectrum
[component intensity
ratio = 0.62; optically
thin (theoretical)
ratio = 0.55]

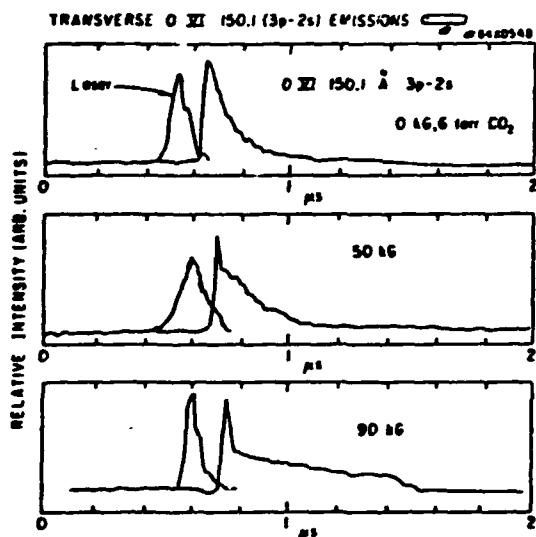


Fig. 6.
Increasing contribution of recombination
peak to total signal shape as
magnetic field is increased.

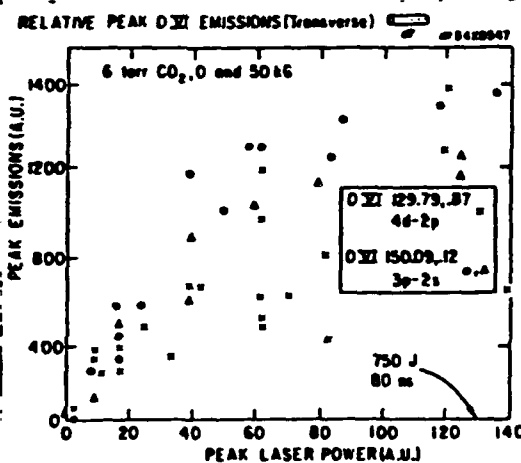


Fig. 7.
Saturation of OVI
emissions at moderate
laser power.

be eliminated by adding 5% Xe to the gas target mix⁴. Time resolved transverse data (Fig. 4) shows population levels which were used to estimate gain of 1.8 cm^{-1} on the 4f-3d transition, based on a Stark broadened linewidth of 0.1 \AA (Ref. 6). The EUV instruments, however, did not have the range to measure the 4f-3d 520 \AA line.

In order to measure population inversions one must be confident that the transitions involved are not optically thick. For this reason we measured the ratio of the time structure components of the OVI 3d-2p transition (Fig. 5). The measured component intensity ratio of 0.62 is close to the optically thin, statistically distributed value of 0.55, so that self absorption was neglected.

The effect of the magnetic field on OVI EUV emissions is shown in Fig. 6. With increasing magnetic field there is faster initial recombination and subsequent longer confinement.

Lending further support to the existence of strong recombination and inversions is the transverse data of Fig. 7, showing an apparent saturation of OVI emissions at moderate laser power. This is consistent with the ionization of OVI to the He-like species and subsequent recombination. The wider scatter of the OVI 129 \AA (4d-2p) points on this graph demonstrates the variation of the 4d-3d population inversion.

The encouraging results in OVI prompted an investigation of other members of the Li-like series. It has been suggested, and demonstrated for LiI and BeII, that the Li-like sequence is well suited for population inversions and gain⁷; for example, 4d-3d population inversions have been measured in AlXI.^{8,9}

In Fig. 8, an axial spectrum for a Ne gas target illustrates a population inversion in NeVIII while Fig. 9 shows time resolved signals and level populations. The variation of the population inversion with Ne pressure is discussed in Ref. 1. As in the case of OVI, trapping of emissions from the lower inversion level of NeVIII were determined to be unimportant (Fig. 10). Here also, the ratio of the fine structure components is close to the optically thin value. However, no enhancement was detected on the lasing transition 4f-3d (NeVIII 292 \AA). In these runs no magnetic field was used so that the inversion may not have been uniformly distributed in the axial direction. Also neutral gas absorption of EUV emission could have played a role. A new gas target is being designed to avoid this problem.

Without any attempt to optimize conditions, 4d-3d inversions were also measured on time integrated spectra (photographic plates) for CIV and FVII using disc targets (carbon and teflon, respectively) with $B=0$ and $B=50 \text{ kG}$ magnetic fields.

In some preliminary runs with Al-disc targets with $B=0$ and $B=50 \text{ kG}$, no population inversions were detected in Li-like AlXI. Plasma radiation in this case may have prevented the temperature from rising high enough to appreciably ionize AlXI to He-like AlXII.

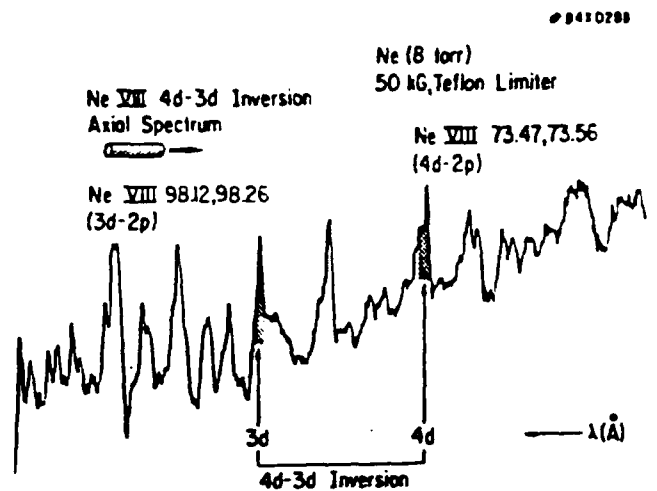


Fig. 8
NeVIII 4d-3d
population inversion
3.7:1. Time
integrated spectrum.

Ne VIII Population Inversion 9 torr Ne 0 kG #84x0546

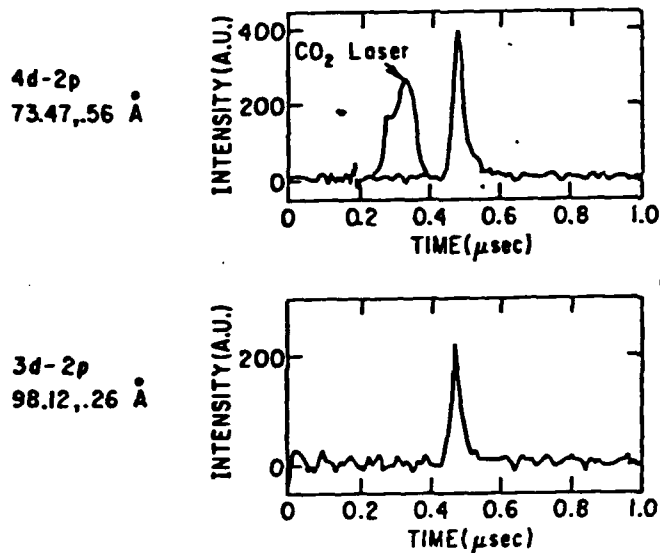


Fig. 9.
NeVIII signals demonstrating
4d-3d population inversion $\approx 5.3:1$.
Column sublevel population densities
are $\bar{n}_{4d} \approx 1.6 \times 10^{12} \text{ cm}^{-2}$ and
and $\bar{n}_{3d} \approx 3 \times 10^{11} \text{ cm}^{-2}$.

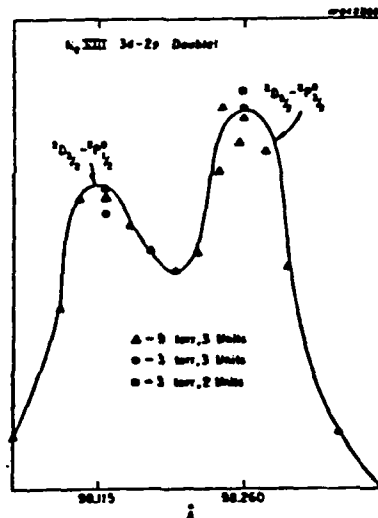


Fig. 10.
Fine structure of
NeVIII 3d-2p
transitions. Peak
values of time
resolved signals in
third order normalized
to the first order.

III. CONCLUSIONS

The plasmas produced using graphite disc targets, with and without Al blades, and with $B=50$ to 90 kG axial magnetic fields have been shown to produce gain-length products of up to about 4.0 as indicated by both time resolved and time integrated data. At present, the effect of the Al blades on observed axial enhancements of CVI 182.17 line radiation is not clear.

Preliminary work has been done with axially oriented carbon fibers. Our best result indicates a gain-length product of about 3.0 . In the future, we will investigate a wider range of fiber lengths and diameters, add aluminum as a deposit on the fiber surfaces (for radiative cooling) and use the magnetic field for confinement.

Population inversions have been measured for $4d$ and $3d$ levels in selected Li-like ions, but no enhancement on the $4f-3d$ transition has been seen as yet.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the valuable technical assistance of D. DiCicco and V. Vasilatos. Thanks are extended to G. Cutsogeorge for excellent help in overcoming noise problems. This work is supported by the U.S. Air Force Office of Research, Contract No. AFOSR-84-0025 and the Department of Energy, Contract No. DE-AC02-76-CHO-3073.

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